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ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF CONCRETE CONTAINING BIOMASS FLY ASH

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Abstract *Concrete production sector is challenged by attempts to minimize the consumption of raw materials and energy and to reduce environmental impact. The use of end-of-life products as cement replacement can allow the production of concrete with the same durability, similar quality properties and with improved environmental performance.*

This work studies the environmental benefits of incorporating different percentages of two types of fly ashes that can be used in concrete as cement replacement, according to the Portuguese context. The results showed that both ashes provide a benefit for the concrete production because it is possible to produce concrete with low Portland cement content and with a better environmental performance while achieving satisfactory mechanical resistance. As already demonstrated for coal fly ash, the use of biomass fly ash seems to be a promising alternative for the replacement of Portland cement.

1. INTRODUCTION

The construction industry is an important economic sector in the European Union. This sector is responsible for the creation of new jobs and leads to the economic growth [1].

Worldwide consumption of concrete is just being exceeded by water. Concrete is the most used material in the construction sector [2–4] and this is because it presents good mechanical and durability properties, is mouldable, adaptable, has a significant fire resistance, is available in most parts of the globe and is affordable [4].

One of the most important components of concrete is cement [5]. It is known that production of cement uses high quantities of raw materials and energy. On the other side, high content of CO_2 is released to atmosphere, and it contributes to the environmental problems related to greenhouse gases emission [2, 4–11].

To reduce the problem associated with the production of concrete, several studies have been dealing with the incorporation of other products that result in a type of concrete with enough performance, or even better, but with lower environmental impact [7, 11]. The introduction of end-of-life products as substitutes of the cement seems to be a good solution for cement substitution [4].

In Portugal, the use of renewable resources, such as biomass, for heat and power production, by combustion, has been increasing [12, 13]. During biomass burning high quantity of ashes is produced and in the last years, this quantity is being increasing with the increase of biomass used [12]. These ashes are classified as solid waste and are in most cases disposed of in landfills.

Previous studies show that the use of pozzolanas from biomass in concrete could have good results [13–17]. The use of biomass fly ashes (BFA) as partial cement substitution leads to the minimization of the utilization of raw materials [12] and a better environmental and economical solution for ash management.

Therefore, it is important to analyze and compare the potential environmental impacts related to the production of plain Portland cement (PC) concrete with the impacts resulting from the manufacture of a concrete incorporating fly ash as raw materials substitution. One of the best approaches to developing this type of studies is to use the life cycle assessment (LCA) method [8]. This method allows the quantification of the potential environmental impacts of products or services and quantifies the input flows, such as energy, water, and materials, and the output flows, including CO_2 emission, solid wastes and liquid wastes [18, 19]. The LCA allows estimating the potential impact on humans and nature and allows identifying areas with improvement potential [18].

2. STUDIED CONCRETE FORMULATIONS

In this study three percentages of cement substitution (20, 40 and 60 %) and ten formulations were studied: FA0, C_FA20, C_FA40, C_FA40, B_FA20, B_FA40, B_FA60, CB_FA20, CB_FA40 and CB_FA60. In the mixture FA0, the processes necessary to produce a PC concrete (only with Portland cement as binder) are considered and this concrete was used as the reference. In the mixtures C_FA20, C_FA40, and C_FA60 (coal fly ashes (FA)) and B_FA20, B_FA40 and B_FA60 (using biomass fly ashes) the processes necessary to produce a concrete with partial cement substitution were considered. The last three mixtures (CB_FA20, CB_FA40 and CB_FA60) are related to the study of environmental impact to produce a concrete with partial cement substitution by a blend of the two types of ashes (at an equal mass content). More detailed information can be found in [20].

3. METHODOLOGY

To evaluate the environmental performance of the several concrete formulations analyzed, the method used in this study followed the phases of an LCA. The comparative analysis and the aggregation of indicators were developed using the multi-criteria decision support Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC) [21, 22]. This methodology is processed in five steps: i) definition of the sustainability indicators; ii) quantification of the indicators (including the life cycle inventory); iii) normalization of the indicators; iv) aggregation of the indicators; and v) sustainable score calculation and global assessment [21, 22].

3.1. Functional and system boundaries

In this study the object of analysis is concrete, and the functional unit is 1 m^3 of concrete. The MARS-SC methodology allows to assess all different life-cycle stages [21, 22], but the boundaries of this work only include the embodied environmental impacts (cradle-to-gate) of the different concrete compositions and the environmental impacts resulting from the transportation of the materials to the concrete plant and their mixing.

3.2. Definition of sustainability indicators

In MARS-SC, the definition of the sustainability indicators depends, above all, on the type of analyzed product or building element and in the aims of the study. In this method the environmental performance assessment is based on the following six environmental impact categories (Table 1): i) Global warming; ii) Ozone depletion; iii) Acidification of soil and water; iv) Eutrophication; v) Photochemical ozone creation; and vi) Depletion of abiotic resources-fossil fuels.

Table 1- Indicators, units and quantification methods

Environmental indicators	Units	LCIA Methods
Global warming (GWP100)	[kg CO_2eq]	CML 2 baseline 2000 V2.05
Ozone layer depletion (ODP)	[kgCFC-11 eq]	CML 2 baseline 2000 V2.05
Acidification potential (AP)	[Kg SO_2 eq]	CML 2 baseline 2000 V2.05
Eutrophication potential (EP)	[kg PO_4eq]	CML 2 baseline 2000 V2.05
Formation potential of tropospheric ozone (POCP)	[kg C_2H_4eq]	CML 2 baseline 2000 V2.05
Abiotic depletion potential of fossil resources (ADP_FF)	[MJ eq]	Cumulative Energy Demand V1.08

3.3. Quantification of sustainability indicators

To quantify the sustainability indicators, it is necessary to develop the inventory analysis primarily [22]. The inventory is used to quantify the inputs (e.g. energy, materials and chemical) and outputs (e.g. emissions and wastes) of the product system [23]. As mentioned before, in this study the production of raw materials, their transportation to the concrete plant and the production of concrete were included in the inventory.

The binder was considered as the sum of cement, coal fly ash and biomass fly ash. Table 2 presents the inventory of the materials and transportation considered for each concrete formulation. The gravel, sand, water and superplasticizer content were the same for each formulation as well as the transportation: 1100, 750, 175 and 8.8 kg respectively and 577.2 tkm (for gravel and sand transportation) and 2.9 tkm for superplasticizer transportation. This inventory took into consideration the specific context of the Portuguese concrete industry. The life cycle analysis software SimaPro 7.3.3 was used to facilitate the quantification of the impact categories [20].

Table 2 - Inventory results of the material and transportation inputs for each concrete (figures per m^3 of produced concrete) [20]

Concrete	FA0	C_FA20	C_FA40	C_FA60	B_FA20	B_FA40	B_FA60	CB_FA20	CB_FA40	CB_FA60	Unit
Material Input											
PC	350	280	210	140	280	210	140	280	210	140	kg
FA		70	140	210				35	70	105	kg
BFA					70	140	210	35	70	105	kg
Transportation Input											
PC	14.4	11.5	8.6	5.7	11.5	8.6	5.7	11.5	8.6	5.7	tkm
FA		11.6	23.1	34.7				5.8	11.5	17.3	tkm
BFA					10.1	20.2	30.2	5.0	10.1	15.1	tkm

The specific consumption of raw materials, energy and fuels and the emissions released to air, water and soil during the cement production of an important Portuguese cement plant, which is located in the south of Portugal, was considered in this study. Considered figures are based in its Environmental Declaration [24]. For this research it was considered that cement used for the preparation of the different concrete formulations was supplied by this cement plant. It was necessary to quantify the impact categories since the environmental declaration did not cover all impact categories required for this study, but only those that are mandatory to declare according to the Portuguese environmental legislation.

Regarding each type of fly ashes, it was needed to make the allocation of flows of the power plant where they were produced. Allocation is necessary in the case of joint co-production, where the processes cannot be subdivided, as in the case of fly ashes production [25]. The allocation shall respect the primary purpose of the processes studied, allocating all relevant products and functions appropriately. Since the main objective of a thermal power plant is to produce electricity and because the great difference in revenue between the electricity and the fly ashes, it is not possible to use an allocation process based on physical proprieties (e.g. mass and volume). Therefore, the allocation process used in this research is based on economic values and it is explained in [20].

Regarding the biomass fly ashes, it is important to highlight that in Portugal this kind of fly ashes are considered a residue and therefore they do not have economic value. For this fact and according to the allocation rules presented in ISO 14040, no flows from the thermal power plant are allocated in the production of biomass fly ashes.

In what respects to the life-cycle inventory of the other used materials (gravel, sand, water and superplasticizer), generic data was used. Since the development of specific environmental information for products is very time and cost consuming and due to the lack of public available specific data for the abovementioned materials, this information was gathered from one the Ecoinvent report V2.2 [26]. The nearest context to the Portuguese was considered for this study. Since the energy consumed during the manufacturing process is the parameter that most influences the life-cycle environmental impact [27] and due to the fact that the Portuguese energy mix is different from the European average [28], a contextualization of the energy used in each process was developed.

In the inventory of the transportation processes the study took into account, the distances between the places of raw materials extraction or raw materials storage facilities and the considered concrete mixing plant. The flows taken into account for the transportation processes were based on the generic values from the Ecoinvent report V2.2.

The inventory related with the production of concrete was quantified taking into account the Environmental Product Declaration (EPD) [29] of a specific Portuguese concrete plant were the different concrete formulations are assumed to be produced. From this EPD, only the flows related to the concrete mixing phase were considered.

3.4. Normalization

To avoid the scale effects in the aggregation of parameters of the different indicators and to minimize the issue that some of the parameters are of the type “higher is better” and others “lower is better” it is necessary to do the normalization of indicators [22]. The normalization was done using the Diaz-Balteiro [30] equation (Equation 1).

$$\overline{P}_i = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \tag{1}$$

In this equation, *Pi* is the value of ith parameter. P_i^* and P_{*i} are the best and worst value of the i^{th} sustainability parameter, among the analyzed products. Normalization converts the values into a scale bounded between 0 (worst value) and 1 (best value) and turns the value of each indicator dimensionless [22].

3.5. Aggregation and global assessment

The aggregation of each environmental indicator in a global indicator that describes the overall environmental performance (NDA) follows Equation 2.

$$N_{DA} = \sum_{i=1}^{n} w_i . \bar{P}_i \qquad (2)$$

The global indicator NDA is the result of the weighting average of each normalized indicator $\bar{P}_i$ and w_i is the contribution of the i^{th} indicator for the overall environmental performance. The sum of all weights must be equal to 1 [22]. For the aggregation, this study considers the default weights of the MARS-SC [21]. The weights are presented in Table 3 and express the relative importance of each environmental impact category in the quantification of the global environmental performance. The weights of the MARS-SC are in line with a study developed by the US Environmental Protection Agency's Science Advisory Board (SAB) [31].

Table 3- Weight for each environmental indicator [21]

Indicator	Weight (%)
GWP	38
ODP	12
AP	12
EP	12
POCP	14
ADP_FF	12

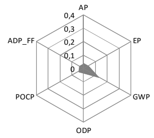
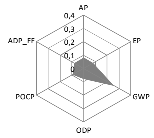
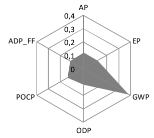
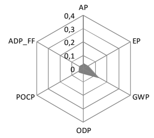
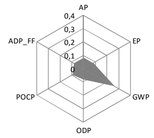
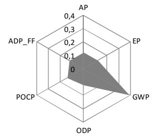
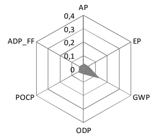
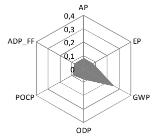
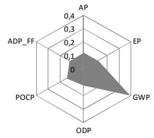
The results are presented in a "radar" or Amoeba diagram, also known as the sustainable profile. In the diagram, the number of rays is equal to the number of indicators that are in analysis. In each sustainable profile, the global performance of each concrete with fly ashes is monitored and compared with the performance of the reference concrete.

4. RESULTS AND DISCUSSION

The quantification of the environmental impacts of 1kg of the different types of binder is discussed and presented in [20].The sustainability profiles and the overall environmental performances are represented in Table 4. In the profiles, the shadowed area represents the performance of each concrete analyzed. At the level of each impact category, the best concrete is the one that has the value nearest to one. It is verified that B_FA60 concrete presents the best environmental performance and normal concrete (FA0) presents the worst performance. The incorporation of fly ashes allows reducing all environmental impacts when compared with the plain cement concrete. The potential environmental impacts decrease with the increase in fly ash content.

So, from these results it is possible to conclude that the use of high content of biomass fly ash increases significantly the environmental performance of concrete production, having a positive contribution to the environmental performance of concrete.

Table 4 - Normalized values that described the sustainability profile adapted from [20]

Concrete	Sustainable Profile	Performances
FA0	-	0.00
C_FA20		0.32
C_FA40		0.65
C_FA60		0.98
B_FA20		0.33
B_FA40		0.66
B_FA60		1.00
CB_FA20		0.32
CB_FA40		0.66
CB_FA60		0.99

5. CONCLUSIONS

In this work, nine different concretes with a different mixture of binder were studied and compared with a plain cement concrete. Fly ashes used alone or blended showed the capability to reduce the environmental impacts of concrete when compared to the conventional concrete. The results showed that the best concrete is the one that have 60% of cement replaced by BFA.

This work also showed that the incorporation of BFA allows a better solution for ashes disposal and that this is a contribution to the development of concrete with improved environmental performance. Despite the good results presented they need to be complemented by experimental studies focusing in the mechanical proprieties of concretes using this new pozzolanic material.

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